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Forecasting Lightning Initiation Using Dual-Polarization Radar and the Lightning Mapping Array in and around Washington, D.C.

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***Abstract*—Prior studies by Woodard [2011], Thurmond [2014], and Travis [2015] show that dual-polarization radar can be utilized to identify the presence of hydrometeors necessary for cloud charging. Travis [2015] discovered two parameters, when used together, produced the best results: Z greater than or equal to 36.5 dBZ and Z_{DR} greater than or equal to 0.31 both at the -10° C level. This study tested the lightning initiation method developed for Cape Canaveral Air Force Station (CCAFS) and NASA Kennedy Space Center (KSC) in Travis [2015] in a new location. The method was tested on 100 isolated, warm season thunderstorms spanning 6 years in and around the Washington, D.C. area. The results of this study concluded that the lightning initiation prediction algorithm from Travis [2015] does not perform well for the Washington, D.C. area. This implies that one lightning initiation algorithm cannot be applied across the entire national NEXRAD network.**

***Keywords*—dual-polarization radar; Lightning Mapping Array, lightning initiation, forecasting lightning**

I. INTRODUCTION

The occurrence of lightning is one of Earth's natural dangers and each day approximately 50,000 thunderstorms occur around the globe [Ahrens, 2014]. Over the past 30 years, the United States has averaged around 55 lightning fatalities and 300 injuries per year [Roeder, 2012; NWS, 2017a]. Although there have been recent reductions in lightning-related injuries and fatalities, lightning continues to remain a deadly and costly weather phenomenon in the United States [Holle, 2016]. Research conducted by the National Lightning Safety Institute suggests realistic lightning costs and losses may exceed $8-10 billion per year in the United States alone [National Lightning Safety Institute, 2014]. Continuing research into this deadly and costly force of nature will allow for additional time to prepare and respond with effective safety measures.

Lightning initiation is among the biggest forecast challenges facing the Air Force's 45th Weather Squadron (45WS). The 45WS is responsible for supporting space launch operations at Cape Canaveral Air Force Station (CCAFS), Kennedy Space Center (KSC) and Patrick Air Force Base (PAFB). Determining the most accurate lightning initiation prediction methods is vital to safeguard these areas, which include over $20 billion in equipment, facilities and over 25,000 personnel [Travis, 2015]. While lightning initiation predictor methods currently exist for the CCAFS/KSC/PAFB area, these methods can be improved upon and possibly applied to different locations to increase lightning forecast accuracy across the country. The 45WS is especially interested in increasing the lead-time of their lightning forecasting while maintaining good skill.

The electrification of a developing single-cell thunderstorm is the result of a combination of several processes. Non-inductive charging is currently the most widely accepted theory as the dominant electrification process within a thunderstorm [Wallace and Hobbs, 2006]. According to Deierling et al [2005; 2008], the production of lightning is directly proportional to mass upward flux of ice crystals and the downward mass flux of graupel. Each of these fluxes is tied to the updrafts and downdrafts of the single-cell thunderstorm. Charge is generated within the cloud when collisions occur between falling graupel and stationary to upward moving ice crystals that make up various portions of the cloud [MacGorman and Rust, 1998]. This vertical charge structure is primarily separated into several distinct regions of opposite charge. In the collision process, graupel (gaining mass through accretion) descends as it becomes too heavy for the updraft to hold aloft and small, lighter weight ice crystals ascend with the updraft. Supercooled water droplets must also be present as they have been experimentally proven to promote significant charge transfer [Reynolds et al., 1957]. During collision, heavier graupel is typically negatively charged while the lighter ice crystal is positively charged [Reynolds et al., 1957]. Under some conditions, the charging is reversed from normal, leading to more frequent positive polarity cloud-to-ground lightning from the core of the thunderstorm. The graupel pellets charge negatively at low temperatures and positively at higher temperatures [Saunders, 2008]. This charging process provides insight into the feasibility of using various dual-polarization radar parameters for the prediction of lightning initiation.

Prior studies by Woodard [2011] and Thurmond [2014] show that dual-polarization radar can be utilized to identify the presence of hydrometeors necessary for cloud charging. These studies also emphasized that a combination of Z and Z_{DR} predictors have the potential to improve forecast skill of lightning onset over methods that rely on Z alone. The most recent lightning initiation research, conducted by Travis in 2015, provided the basis for this study as he further describes the use of dual-polarization radar to improve lead times for lightning onset. Travis [2015] highlighted that Z_{DR} is the preferred parameter to use in conjunction with Z values as elevated Z_{DR} values are indicative of supercooled water droplets and wet ice particles. More precisely, the mixed phase hydrometeors, which are necessary for cloud electrification, create a well-defined Z_{DR} column. The results of Travis [2015] confirmed that using both Z and Z_{DR} predictors increases the Probability of Detection (POD) and lead time while decreasing the False Alarm Ratio (FAR). Travis [2015] discovered two parameters, when used together, produced the best results: $Z \geq 36.5$ dBZ coupled with a $Z_{DR} \geq 0.31$ both at the -10°C thermal level.

While prior studies have primarily focused on atmospheric conditions preceding lightning initiation, more work is needed to apply dual-polarization parameters to this challenging problem. This study will verify the lightning initiation method developed by the Air Force Institute of Technology for CCAFS and KSC by Travis [2015]. The best performing thresholds for the CCAFS/KSC area based on forecast metrics and lead time will be applied to the Washington, D.C. region. If this lightning initiation method verifies well at this new location, that will build confidence for use of the method at CCAFS/KSC and lend credence for use at other locations and eventual implementation as a new product in the Next Generation Weather Radar (NEXRAD) network.

II. DATA AND METHODOLOGY

A. Data

Three weather radars provide coverage of the Washington, D.C. area. The Sterling, VA (KLWX) radar located approximately 25 miles northwest of Washington, D.C., the Dover Air Force Base, DE (KDOX) radar located approximately 110 miles east of Washington, D.C. and the Wakefield, VA (KAKQ) radar located approximately 138 miles southeast of the Washington, D.C. area. These radars are shown in Fig. 1. For this study, radar data was pulled exclusively from the KLWX radar as it provided optimal coverage of all thunderstorm cases analyzed. Archived Level-II radar data was downloaded from the National Centers for Environmental Information (NCEI) NEXRAD Data Inventory.

Fig. 1. Map showing the radars surrounding the Washington, D.C. area. Washington, D.C. is denoted by a blue star.

Although this study builds upon the work of Travis [2015], a different dataset will be utilized for lightning detection. More specifically, the Lightning Mapping Array (LMA) will be used instead of the Four Dimensional Lightning Surveillance System (4DLSS). The LMA network located in Washington, D.C. locates the total lightning activity from a thunderstorm using a network that consists of ten sensors in and around the D.C. metropolitan area shown in Fig. 2. The Washington, D.C. LMA is a joint demonstration project involving the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and New Mexico Tech. Archived LMA data was downloaded from the DC LMA Post-Processed Data Archive.

A LMA is a network of time-of-arrival geolocation sensors that passively receive very high frequency (VHF) impulses emitted as dielectric breakdown occurs within thunderstorms, especially the small fast components of a lightning flash such as stepped leaders [Wilson, 2005; Wiens, 2007; Thomas et al., 2004]. It uses the difference in time-of-arrival of these signals from multiple pairs of sensors to locate the discharge in three physical dimensions. As the lightning channel develops, a map of the discharge path is produced, including channels within the cloud. Each flash of lightning creates a cluster of individual source detections. A source-to-flash clustering algorithm [Thomas et al., 2004] is then used to automatically identify flashes as sensed with the mapping array using time-space separation thresholds [Chmielewski and Bruning, 2016]. Processing for the LMA is done in one second segments and the arrival times at all stations within the network are sorted sequentially by time [Thomas et al., 2004].

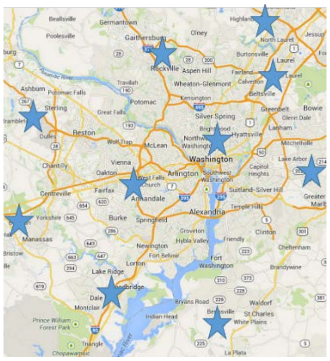

Fig. 2. Map showing the locations of the LMA sensors surrounding the Washington, D.C. area.

B. Methodology

An initial dataset of 230 convective cells was collected using a quick-look method to eliminate and retain cases on the NCEI Interactive Radar Map Tool. These cases all span a six year period from 2012-2017. Only warm-season (May-September) cases were considered. First, the case date was analyzed for convective features. If a case date was dominated by a large multicellular structure or a squall line, then it was not considered for analysis. Specific intensity criteria were not used when compiling the initial database with the Interactive Radar Map Tool as this tool does not allow the user to see exact *Z* values of specific cells. Cases that passed the initial dataset inspection were recorded.

Using the GR2Analyst Version 2.60 software, the 230 convective cell initial dataset was narrowed down to a final dataset. Implementing a strict rack-and-stack method cut the initial dataset of 230 convective cells into a final dataset of 100 convective cell cases. Prior studies conducted by Woodard [2011], Thurmond [2014], and Travis [2015] utilized the Larsen area method of radar analysis and lightning initiation location [Larsen and Stansbury, 1974] to determine which cells to further investigate. For this study, the cells were analyzed for a Larsen area defined by a horizontal Z threshold ≥ 30 dBZ at -10°C. This Z value indicates substantial cellular development of a precipitation core based on the size distribution of hydrometeors associated with cloud electrification. The -10°C thermal level is significant to thunderstorm charge structure as it indicates the lower level of the main charging region and mixed phase region of the main negative charge zone. Once the convective cell was determined to be significant enough to potentially produce lightning, the next step was to ensure it was isolated. The convective cell was considered isolated if there were no storms with connecting *Z* values greater than 15 dBZ [Patton, 2017].

The next step is to verify that each of the individual convective cells fall within 85 km of the KLWX radar as NOAA defines this range as the range for optimal radar coverage [NOAA, 2017a]. Cases must also be within 100 km of the center of the Washington, D.C. LMA network. Chmielewski and Bruning [2016] found that the predicted flash detection efficiency exceeded 95% within 100 km of all LMA networks. Fig. 3 shows the GR2Analyst map with both range ring overlays. Each of the convective cells must fall within the overlap of the two range rings to be considered for further analysis. After verifying the location of the cases, the raw LMA data was read to determine the health of the Washington, D.C. LMA network. The final criteria of the case collection rack-and-stack method was to analyze the health of the KLWX radar.

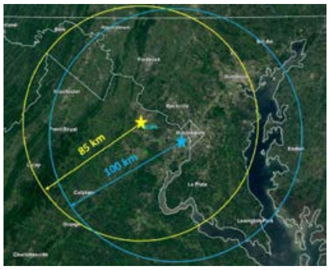

Fig. 3. Map of the KLWX radar range ring (yellow) and the Washington, D.C. LMA range ring (blue) overlays. The stars denote the range ring centers.

Table I. Summary of the possible forecast outcomes based on whether the event is forecasted and whether it is observed. Table developed by Travis [2015] from Jolliffe and Stephenson [2003].

Event Forecast	Event Observed	
	Yes	No
Yes	Hit	False Alarm (FA)
No	Miss	Correct Rejection (CR)

Prior to testing the Travis [2015] lightning initiation criteria, the LMA data was interrogated to determine whether or not a lightning strike occurred within each of the 100 convective cells using MATLAB. Following the verification of lightning initiation, heights of the -10°C thermal levels were collected for each case using soundings from the University of Wyoming. Once the necessary steps were taken to build a complete and robust dataset, the analysis of the highest performing lightning initiation prediction criteria from Travis [2015] for CCAFS/KSC was conducted in the Washington, D.C. area.

To begin the analysis of these thresholds, radar data was ingested into GR2Analyst. The case was located on the main base reflectivity interface, and the cross-section tool was then used to analyze a slice of the cell's base reflectivity. This process allowed the user to determine if the $Z \geq 36.5$ dBZ threshold at -10°C was met at any point. The volumetric display function with an isosurface *Z* value set at 36.5 dBZ was also utilized to further verify that the *Z* threshold was met. After the analysis of Z, the cross-section tool was again utilized to determine if the $Z_{DR} \geq 0.31$ threshold was met at -10°C. Unlike *Z* verification, the volumetric display tool could not be used in the Z_{DR} analysis as this feature is only available for base Level-II products. If the predictor threshold was met and the cell produced lightning, then it was recorded as a "hit". If the threshold was met but the cell did not produce lightning, then a "false alarm" was recorded. If a cell did not reach the predictor threshold but still produced lightning, then it was marked as a "miss". Cells that did not hit the predictor threshold and did not produce lightning were recorded as a "correct rejection". A summary of the forecast outcomes for the analysis is given in Table I.

III. ANALYSIS AND RESULTS

A. Forecast Metrics Comparison

The performance of the lightning initiation predictor method was measured using forecast metrics utilized in Travis [2015]. By using the same metrics, a direct comparison between the studies can be done and highlights the applicability of the lightning prediction algorithm when used in a new location. Table II summarizes the results of this comparison. The arrows indicate whether the metric for this study was above or below the metric calculated in Travis [2015]. Each of the arrows are in red to indicate that the metric change showed a decrease in forecast skill.

For this study, there were 65 cases in which lightning occurred and 35 cases where lightning did not occur. Additionally, there were 26 hits, 10 misses, 38 correct rejections, and 26 false alarms. The breakdown of these forecast outcomes helps explain the forecast metric results. The first metric, POD,

Table II. Table summarizing the results of the analysis. The red arrows indicate whether the metric is higher or lower for Washington, D.C. than it was for CCAFS/KSC. The asterisk for OUI represents the use of the modified OUI equation rather than the OUI equation used in Travis [2015].

	Washington, D.C.	CCAFS/KSC
POD	0.7222 ↓	0.8889
FAR	0.5000 ↑	0.0588
PFA	0.4063 ↑	0.0769
TSS	0.3160 ↓	0.8120
Mean OUI*	0.5108 ↓	0.7111
Median OUI*	0.4849 ↓	0.6848

provides insight into the correctly forecasted lightning occurrences. Although the POD provides useful information, it is limited in measuring the overall skill of a forecast as it does not take false alarms into account [Jolliffe and Stephenson, 2003]. For perfect skill, a value of 1.0 is needed. CCAFS/KSC had a POD of 0.8889 while Washington, D.C. had a lower value of 0.7222, indicating a higher hit rate for CCAFS/KSC than for the Washington, D.C. area.

The next metric, FAR, provides the probability of a false alarm when an occurrence is predicted [Jolliffe and Stephenson, 2003]. Similarly to POD, FAR is not a useful skill on its own due to the dependence on the amount of hits. CCAFS/KSC had a FAR of 0.0588 while Washington, D.C. had a value that was almost ten times higher at 0.5000. The optimal value for FAR is 0.0, so the performance of the lightning prediction algorithm based on this metric was much worse for the Washington, D.C. area. The Probability of False Alarms (PFA) is another way to quantify the false alarms. This metric compares the false alarms with correct rejections [Jolliffe and Stephenson, 2003] and only provides limited insight into forecast reliability as it is dependent on correct rejections in the denominator. CCAFS/KSC had a PFA of 0.0769 while Washington, D.C. had a value over five times higher at 0.4063. The high value can be attributed to the number of false alarms resulting in the analysis of this study. A PFA of 0.0 is optimal, so the lightning prediction algorithm showed less skill with this metric in the Washington, D.C. area.

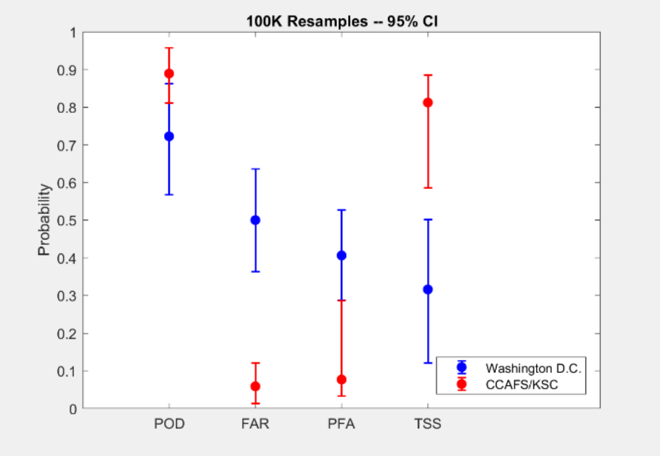

Fig. 4. 95% confidence intervals of four standard forecast metrics for CCAFS/KSC (red) and Washington, D.C. (blue). The confidence intervals were created using the bootstrap technique with 100,000 resamples and values from the original samples, identified by the closed circles. Graphic created using MATLAB.

The final standard metric, True Skill Statistic (TSS), accounts for all possible forecast outcomes from Table I. CCAFS/KSC had a TSS of 0.8120, while Washington, D.C. had a value that was less than half that value of 0.3160. A TSS value of 1.0 is desired as it indicates perfect skill, so the lightning prediction algorithm again performed worse for the Washington, D.C. area. Fig. 4 gives the 95% confidence intervals of the four standard forecast metrics for CCAFS/KSC and the Washington, D.C. area. This figure shows that the POD is the only metric with overlap for the two studies. Overall, Fig. 4 shows with confidence that the standard forecast metrics for Washington, D.C. are statistically different than those of CCAFS/KSC.

In addition to standard forecast metrics, the Operational Utility Index (OUI) was also analyzed. This metric is a nonstandard metric that was created by the 45WS to determine the operational utility of lightning forecast algorithms [Travis, 2015]. The OUI allows the simultaneous optimization of several forecast metrics and lead time. OUI calculations combine the POD, TSS, PFA, and average lead time, in addition to a weighting scheme that reflects the operational priorities of the 45WS. The OUI is normalized by the sum of weights so that it varies from 0 to 1, with 1 being perfect. OUI is defined as:

$$OUI^* = \frac{(3*POD)+(2*TSS)+\left(2*\left(\frac{LeadTime}{MaxLeadTime}\right)\right)+(1*(1-PFA))}{8} \tag{1}$$

where OUI* represents the modified OUI, LeadTime is the average lead time of a forecast algorithm, and MaxLeadTime is the maximum lead time achieved by the same forecast algorithm for a given analysis. This equation is slightly different than the OUI equation used by Travis [2015]. MaxLeadTime was put in the denominator of the lead time term in place of the 30 minutes used by Travis [2015] to allow for a more accurate normalization. Using the updated OUI* equation, the OUI* values were recalculated for Travis [2015] from his original dataset. CCAFS/KSC had a mean OUI* of 0.7111 and a median OUI* of 0.6848 while Washington, D.C. had a mean OUI* of 0.5108 and a median OUI* of 0.4849. The lower values found in Washington, D.C. indicate that the lightning prediction algorithm had less operational skill at this location. Fig. 5 provides the 95% confidence intervals for the OUI* values at CCAFS/KSC and Washington, D.C. and shows no overlap of the mean OUI* values for the two studies. Only the far edges of the 95% confidence intervals are near one another, indicating that the OUI* value found for Washington, D.C. is not statistically similar to the value for CCAFS/KSC. Assuming lead time and maximum lead time being equal, Washington, D.C. has the lower POD, lower TSS, and higher PFA which all act to lower the OUI*. The PFA for Washington, D.C. is much higher due to the high number of false alarms (26% of the dataset). This finding implies that the Travis [2015] criteria is too easily met in the Washington, D.C. area and that the threshold for *Z* should be higher than 36.5 dBZ. Overall, none of the forecast metrics were close, so in terms of forecast metrics, the Travis [2015] lightning initiation prediction algorithm does not work well in the Washington, D.C. area.

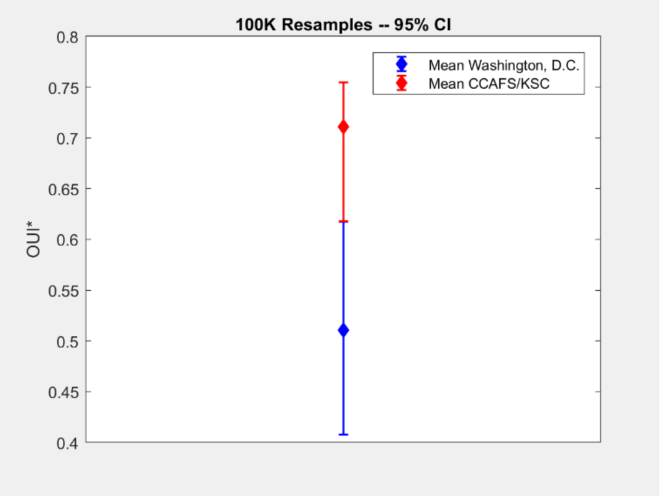

Fig. 5. 95% confidence intervals of the mean OUI* (modified OUI) for CCAFS/KSC (red) and Washington, D.C. (blue). The confidence intervals were created using the bootstrap technique with 100,000 resamples and values from the original samples, identified by the closed circles. Graphic created using MATLAB.

B. *Lead Times Comparison*

Along with forecast metrics, the comparison of lead times found in this study and Travis [2015] provides valuable insight into the performance of the lightning prediction algorithm at a new location. Fig. 6 provides the 95% confidence intervals for the mean lead times. This figure shows that the mean lead times are statistically similar (indicated by significant overlap) and that Washington, D.C. had slightly superior lead times. The same result was found for the median lead times (not pictured). Overall, there is no significant difference between the mean and median lead times for Washington D.C. and CCAFS/KSC.

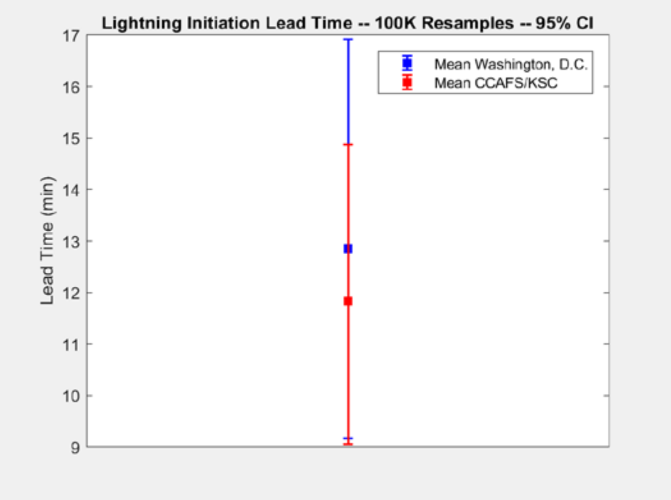

Fig. 6. 95% confidence intervals of the mean lead times for CCAFS/KSC (red) and Washington, D.C. (blue). The confidence intervals were created using the bootstrap technique with 100,000 resamples and values from the original samples, identified by the closed circles. Graphic created using MATLAB.

IV. CONCLUSIONS

A. *Summary*

Lightning initiation is a danger to both life and property and has the potential to cause damage, injuries and even fatalities. Accurate forecasts of thunderstorms are vital for aviation, space launch, and overall public safety. The 45WS faces the difficult task of determining the most accurate lightning initiation prediction methods to protect over $20 billion in equipment, facilities and over 25,000 personnel in and around CCAFS/KSC/PAFB [Travis, 2015]. Although useful lightning initiation prediction algorithms exist for this area, these methods can be improved and possibly applied to new locations to increase the forecast accuracy of lightning nationwide. The 45WS is especially interested in increasing the lead time of their lightning onset forecasting methods while maintaining good skill.

Prior studies by Woodard [2011] and Thurmond [2014] determined that Z predictors, when used in conjunction with Z_{DR} predictors, improve the forecast skill over methods that relied on Z alone. Travis [2015] also confirmed that the implementation of dual-polarization added skill to lightning initiation forecasts. The highest performing lightning prediction algorithm found by Travis [2015] was $Z \geq 36.5$ dBZ paired with $Z_{DR} \geq 0.31$ dB both at the -10°C thermal level. The results of Travis [2015] showed that Z_{DR} is the preferred dual-polarization predictor to use with Z for the improvement of lightning initiation forecasts due to elevated Z_{DR} values indicating wet ice particles and supercooled water droplets. These mixed phase hydrometeors aid in cloud electrification within a developing updraft, and generate a Z_{DR} column as discussed in Kumjian [2013b].

Fig. 4 concludes with confidence that the standard forecast metrics for Washington, D.C. are statistically different than those of CCAFS/KSC. For OUI*, Fig. 5 depicts no overlap of the mean OUI* values for the two studies. The far edges of the 95% confidence intervals are near one another, indicating that the Washington, D.C. value is not statistically similar to the value for CCAFS/KSC. This finding implies that the Travis [2015] criteria are too easily met in the Washington, D.C. area resulting in more false alarms and that the threshold for Z should be higher than 36.5 dBZ. In terms of forecast metrics, the Travis [2015] lightning initiation prediction algorithm does not perform well for the Washington, D.C. area. Although the forecast metrics were different for the two studies, the lead times were quite similar. Fig. 6 indicates that the mean lead times are statistically similar. Ultimately, there is no significant statistical difference between the mean and median lead times reported in Washington D.C. and CCAFS/KSC. To the authors knowledge, no other studies have found these same forecast metric and lead time results.

The hope was that the lightning initiation thresholds would be similar for CCAFS/KSC and Washington, D.C. despite the different climates. It was hypothesized that using temperature as the vertical coordinate allows the physics to be the same. The heights of the electrification and charge separation occurrences will vary, but the temperatures will be the same. Therefore, one expects the same thresholds for moisture, updraft, and cell volume to generate lightning, as long as temperature is used as the vertical coordinate. One explanation for this difference could be the role of aerosols in the electrification process and how this changes between differing climates. The Washington, D.C. area has a much greater population density than the CCAFS/KSC/PAFB area according to data from the 2010 Census [United States Census Bureau, 2010]. More people living in an area could be indicative of the production of more aerosols. Ice nuclei (aerosols) could facilitate more charge separation in the D.C. urban environment where more aerosols are present than the tropical environment found along the central coast of Florida.

The differing forcing mechanisms present in central Florida and Washington, D.C. could also provide insight into the lightning prediction algorithm performance differences. Washington, D.C. is characterized as a baroclinic environment while Florida is more barotropic. Distinct air mass regions exist within baroclinic environments and fronts separate the warmer from colder air causing clear density gradients. Low pressure troughs (mid-latitude cyclones) and the polar jet can also be found in a baroclinic environment as this environment is typically located in the mid-latitudes. Simply put, the atmosphere is out of balance in a baroclinic environment [Ahrens, 2014; Wallace and Hobbs, 2006]. In contrast, barotropic regions are characterized by a lack of fronts and uniform temperature distribution. The southeastern United States in the summer where each day brings about the same weather is the ideal example of a barotropic environment.

The results of this study conclude that the lightning initiation prediction algorithm from Travis [2015] does not perform well for the Washington, D.C. area. This implies that one lightning initiation prediction algorithm cannot be applied across the entire national NEXRAD network. The lightning initiation prediction algorithm must be modified depending on climate.

B. *Future Work*

Although this study provided new insight into the difficult problem of forecasting lightning initiation, more work must be done to further investigate this challenging task. To increase the overall confidence level of this study, the convective cell dataset could be expanded beyond 100 cases. For simplification of this study, which would allow for the analysis of more convective cells, the manual analysis process of using GR2Analyst could be automated. More specifically, a Storm Cell Identification and Tracking (SCIT) algorithm could be developed. This study could also be expanded by testing the lightning initiation prediction algorithm in different geographical locations such as the mountains, inland plains, desert, or Pacific Coast. Additionally, this study could be recreated using a different location's LMA network (e.g. Oklahoma, Alabama).

Further research could be conducted on this topic by including additional dual-polarization parameters, specifically Level-III products such as the Hydrometer Classification Algorithm (HCA). Since the presence of graupel and ice particles are necessary to the cloud charging process, identification of these hydrometeors could be helpful for forecasting lightning initiation. An algorithm similar to the one used for lightning cessation in Patton [2017] could potentially be modified to create a new method for the prediction of lightning initiation. In addition to the inclusion of different dual-polarization parameters, the Z and Z_{DR} thresholds currently used could be adjusted and retested. This approach would help determine the optimal values for the Washington, D.C. area as the current thresholds are too low and were too easily met. Although the results of this study highlight the applicability of a current lightning initiation prediction algorithm, additional research must be conducted to continue the improvement of lightning initiation forecasts.

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